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R.J. Staker

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ABSTRACT

This report demonstrates the application of a Bayesian Belief Network decision support method for Force Level Systems Engineering to a collection of projects related to Aerospace Surveillance and Battle Management. The proposed method is used to determine the most credible combinations of these projects, and the most plausible evolutions of the force structures that they deliver over time. Since the analysis is based on strictly limited information, the results that are obtained are of a highly tentative nature. Nevertheless, the potential utility of such an approach is convincingly demonstrated.

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EXECUTIVE SUMMARY

The problem of developing and sustaining a highly capable defence force to meet the diverse needs of a medium-sized democratic nation such as Australia is an extremely complex onerous one, particularly in view of the plethora of challenges and ambiguities posed by the political circumstances of the twenty-first century, the rapid rate of technological advancement of military systems, and the relatively modest level of funding available. One way of maximising the potential performance of a defence force is to ensure that its assets are capable of cooperating cohesively together as a highly effective system-of-systems. Achievement of this goal may be fostered through the application of suitable Force Level Systems Engineering (FLSE) principles.

A particularly salient feature of systems-of-systems is the presence of multiple stakeholders and decision-makers. Sophisticated and robust force-level systems design methods that can effectively match the needs of disparate stakeholders to the potentially available options are required in order to alleviate the task confronting decision-makers. However, certain results from social choice theory and game theory have implications for the ways in which stakeholders' preferences may validly be aggregated. In addition, the networked nature of systems-of-systems renders evaluation methods that rely on a strictly hierarchical decomposition of the decision problem unsuitable.

These two aspects suggest that belief network methods may be more suitable for treating systems-of-systems questions than are more familiar evaluation methods. The aim of this report is to illustrate how certain Bayesian Belief Network techniques might be applied to FLSE design decisions. The method is intended to be compatible with a wide variety of project management and systems engineering process models, and, thus, there is no particular preferred process. However, some specific features that a process suitable for treating systems-of-systems questions should possess are mentioned in passing.

In general, the procedure involves eliciting the needs of the stakeholders and then suggesting possible solutions that seem to best conform to those needs for closer consideration by the stakeholders and decision-makers, by means of automated reasoning. The particular case that is considered as an example here is that of Aerospace Surveillance and Battle Management (ASBM). A number of legacy assets that form the current ASBM system-of-systems, and projects which will transform the current asset configuration into its future form, have been identified and form the basis of the analysis. The proposed method is used to determine the most credible combinations of the projects, and the most plausible evolutions of the force structures that they might deliver into service, over time.

As it may reasonably be assumed that it is only ever necessary to actually *commit* to an option for the first, impending decision epoch, selection of the most credible option for the first decision epoch over the entire *ensemble* of asset configuration trajectories is more appropriate than assuming that the most credible trajectory will always be the one to ensue. A decision that is made in this way will be termed a *best prospects* decision,

since it attempts to cater for a wide range of possible future developments. This may in general be different from the initial choice on the most credible trajectory.

The rationale for preferring the best prospects option, rather than the initial choice for the most credible trajectory, is that this should usually result in there being more relatively high credibility alternative trajectories on into the future, thus providing greater flexibility as stakeholder needs and preferences undergo future revision. Consequently, the best prospects decision sacrifices some initial credibility about the alternative that is selected in the interests of greater future flexibility. Once the best prospects decision has been determined, the most credible subsequent asset configuration trajectory for the succeeding time periods may be computed to provide a provisional road-map for the anticipated way ahead.

Since the analysis described in this report has been based on strictly limited information, the results that are obtained are of a highly tentative nature. Furthermore, in order to employ the method to its greatest advantage, the ASBM projects would need to be considered in conjunction with the other major projects, such as Air 6000 and Sea 4000, with which they are intimately intertwined. Nevertheless, the potential utility of such an approach is convincingly demonstrated.

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ADF Australian Defence Force

AEW&C Airborne Early Warning and Control

ASBM Aerospace Surveillance and Battle Management

BBN Bayesian Belief Network

CRU Command and Reporting Unit

DCP Defence Capability Plan

DMO Defence Materiel Organisation

FLSE Force Level Systems Engineering

FY Financial Year

GBAD Ground-Based Air Defence

JORN Jindalee Operational Radar Network

MCRU Mobile Command and Reporting Unit

MSOC Mobile Sector Operations Centre

OCD Operational Concept Document

SBS Space-Based Surveillance

GH Global Hawk

1 Introduction

The problem of developing and sustaining a highly capable defence force to meet the diverse needs of a medium-sized democratic nation such as Australia is an extremely onerous and complex one, particularly in view of the plethora of challenges and ambiguities posed by the political circumstances of the twenty-first century, the rapid rate of technological advancement of military systems, and the relatively modest level of funding available. One way of maximising the potential performance of a defence force is to ensure that its assets are capable of cooperating cohesively together as a highly effective system-of-systems. This goal may be fostered through adopting suitable Force Level Systems Engineering (FLSE) principles.

A particularly salient feature of systems-of-systems is the presence of multiple stakeholders and decision-makers. Sophisticated and robust force-level systems design methods that can effectively match the needs of disparate stakeholders to the potentially available options are required in order to alleviate the task confronting decision-makers. However, certain results from social choice theory and game theory have implications for the ways in which stakeholders' preferences may validly be aggregated. In addition, the networked nature of systems-of-systems renders evaluation methods that rely on a strictly hierarchical decomposition of the decision problem unsuitable. These two aspects suggest that Bayesian Belief Network (BBN) methods may be more suitable for treating systems-of-systems questions than are more familiar evaluation methods

The aim of this report is to illustrate how BBN techniques might be applied to assist in making FLSE design decisions. The particular case of Aerospace Surveillance and Battle Management (ASBM) is considered. The techniques in question have been introduced in a preceding report and several published papers. papers [1, 2, 3]. Further background on BBN techniques, in general, may be obtained from the books by Pearl and Neapolitan [4, 5].

1.1 Process

The method to be described is intended to be compatible with a wide variety of project management and systems engineering process models, and consequently there is no particular preferred process. On the other hand, there are several important features that a process suitable for treating systems-of-systems questions ought to possess. One of these is that there should be far more assiduous attention to the human dimensions of the situation than would typically be the case in a more conventional systems engineering approach. Of course, it is necessary, at the same time, to ensure that the objective realities of the situation are properly taken into account.

In dealing with systems-of-systems questions, the presence of multiple stakeholders and decision-makers is a fundamental issue that needs to be appropriately accommodated. This contrasts with conventional systems engineering processes where it is generally assumed that there is one single, predominant decision-maker whose wishes must always be paramount. One aspect of dealing with this issue is to ensure that fairness and transparency are provided for all stakeholders. This assists in promoting the choice of the best decisions for the system-of-systems, as a whole, rather than allowing the available resources

to be covertly monopolised by the most influential stakeholders, to the detriment of total capability.

A further important feature is that extensive interaction between the stakeholders should be catered for to enable tacit and implicit knowledge about their joint, combined needs to be incrementally discovered and elicited. Another is that continuous learning from the outcomes of past decisions should be supported in order to allow the quality of decision-making to be progressively improved. Other features which should be considered are facilitation of the collaboration of geographically dispersed stakeholders, and effective management of large quantities of complex information, in order to allow this to be efficiently shared and utilised.

In general terms, the method involves eliciting the needs of the stakeholders and then generating several of the possible solutions that would seem to best conform to those needs for more intensive consideration by stakeholders and decision-makers, in an iterative fashion. Iteration is important as the stakeholders' understandings of their individual and shared needs may mature through deeper reflection on the problem and the proposed solution options. Another reason for the importance of iteration is to accommodate changes in the stakeholders' needs that may arise due to changing circumstances.

Naturally, the process that has been followed in producing this report, which merely seeks to demonstrate the capabilities of the more technical portion of the proposed method in a realistic, but limited, example, is substantially different from any which might be followed in an actual application.

1.2 Information Requirements

The information that would normally be required in order to properly apply the method to be described here is listed below.

1. A list of the stakeholders affected by the capability under investigation.
2. The decision epochs to be considered.
3. The needs of each of the stakeholders that the capability will be expected to address, according to each epoch and to each stakeholder.
4. Details of the alternative assets that will, or may be, available for procurement, according to each epoch.
5. Details about supporting data links that might be required, according to each epoch.
6. Information about the stakeholders' preferences.

For items 4 and 5 some measure of plausibility is required, ideally in the form of a credibility figure. Item 6 needs to be captured in the form of a BBN fragment. It may be possible to glean a good deal of the necessary information from high-level systems engineering documents, such as the Operational Concept Documents (OCDs) for the systems concerned. However, this will generally need to be supplemented with direct elicitation of additional information from the stakeholders and relevant experts.

Table 1: Information Sources

No.	Source	Ref.
1.	Capability Systems/Battlespace Management Project List	[6]
2.	Public Release Defence Capability Plan	[7]
3.	DMO Project Web Site	[8]

Table 2: Relevant Projects

No.	Area	Project	Title	Abbrv.
1.	AIR	5077	Project WEDGETAIL	AEW&C
2.	AIR	5333	2 CRU and 3 CRU Replacement (VIGILARE)	Vigilare
3.	AIR	5405	Mobile Sector Operations Centre	MSOC
4.	JP	117	ADF Ground-based Air Defence Weapon System	GBAD
5.	JP	2025	Jindalee Operational Radar Network	JORN
6.	JP	2044	Space-based Surveillance Capability	SBS
7.	JP	2062	Global Hawk	GH

1.3 Information Sources

Unfortunately, it has been necessary to limit the information on which this report is based to a list of projects relevant to ASBM, the public Defence Capability Plan (DCP), and the projects web site maintained by the Defence Materiel Organisation (DMO). Thus, a considerable amount of guesswork has been required in order to be able to generate some results, and, consequently any conclusions that are reached must be regarded as being of an extremely tentative nature. The information sources that were employed are listed in Table 1. The OCDs for several of the systems concerned were obtained as this report was being finalised, and thus at a stage when it was too late for them to be used as a basis for the work. However, a brief perusal of them would suggest that the guesses made in creating the example used in this report were not too wildly divorced from reality.

Source 1 lists a number of projects, some of which have in-service dates around the present date, and some of which, such as the replacement of radar transmitters and radio systems, seem to relate to a considerably greater level of detail than the majority of the others. Such relatively simple upgrades have been assumed to already be included in the Period 0 base-line asset configuration. Some of the other projects listed are very vaguely described, or are of a research nature, and have consequently been omitted from further consideration. This process of elimination has reduced the set of relevant projects for the purposes of this report to those shown in Table 2.

1.4 Problem Formulation

The question examined in this report is the most credible evolution of the ASBM system-of-systems under tight cost constraints. Certain earliest decision dates for these projects have been postulated in the DCP [7]. Here it is assumed that it is possible for the decision dates to be postponed beyond those stipulated in the DCP, but that it is not possible to bring them forward.

The aim is to characterise the ensemble of asset configuration trajectories over several periods that most credibly meet the stakeholders' needs under these circumstances, and hence to identify the most propitious option to select at the next impending decision epoch by means of credibilistic inference. A decision made in this way will be termed a *best prospects* decision.

2 Scenario

2.1 Stakeholder Preferences

It has been assumed that there are just two stakeholders involved. Stakeholder A may be taken to represent a hypothetical commander who may have to conduct a campaign using the assets that are provided. Stakeholder B may be taken to represent the head of finance who aspires to restrict defence expenditure to lie within affordable limits.

2.1.1 Stakeholder A

In order to concord with the list of projects given in Table 2, it has been assumed that the needs of a commander that should be provided for by an ASBM system-of-systems are the following.

1. Air space surveillance.
   (a) Long range surveillance.
   (b) Medium range surveillance — lesser surveillance range and less comprehensive coverage, possibly being cued by long range surveillance, but increased probability of detection, discrimination and accuracy.
   (c) Local surveillance — limited to line-of-sight range from fixed ground locations, but detailed, comprehensive and precise.
2. Point defence.
3. Airborne communications relay.

2.1.2 Value Network

The various ways in which the individual assets contribute towards the needs of the hypothetical commander are represented by the value network shown in Figure 1. The network approximates to the form of a tree, with each asset contributing to a particular function. However, it has been assumed that the AEW&C and Global Hawk assets contribute to both medium range air surveillance and airborne communications relay functions. Thus, the network is, in fact, of more general form. Tables A1–A13 in Appendix A give the numerical credibility values that are used to reflect the relative merits of the assets under consideration in performing each of the desired functions.

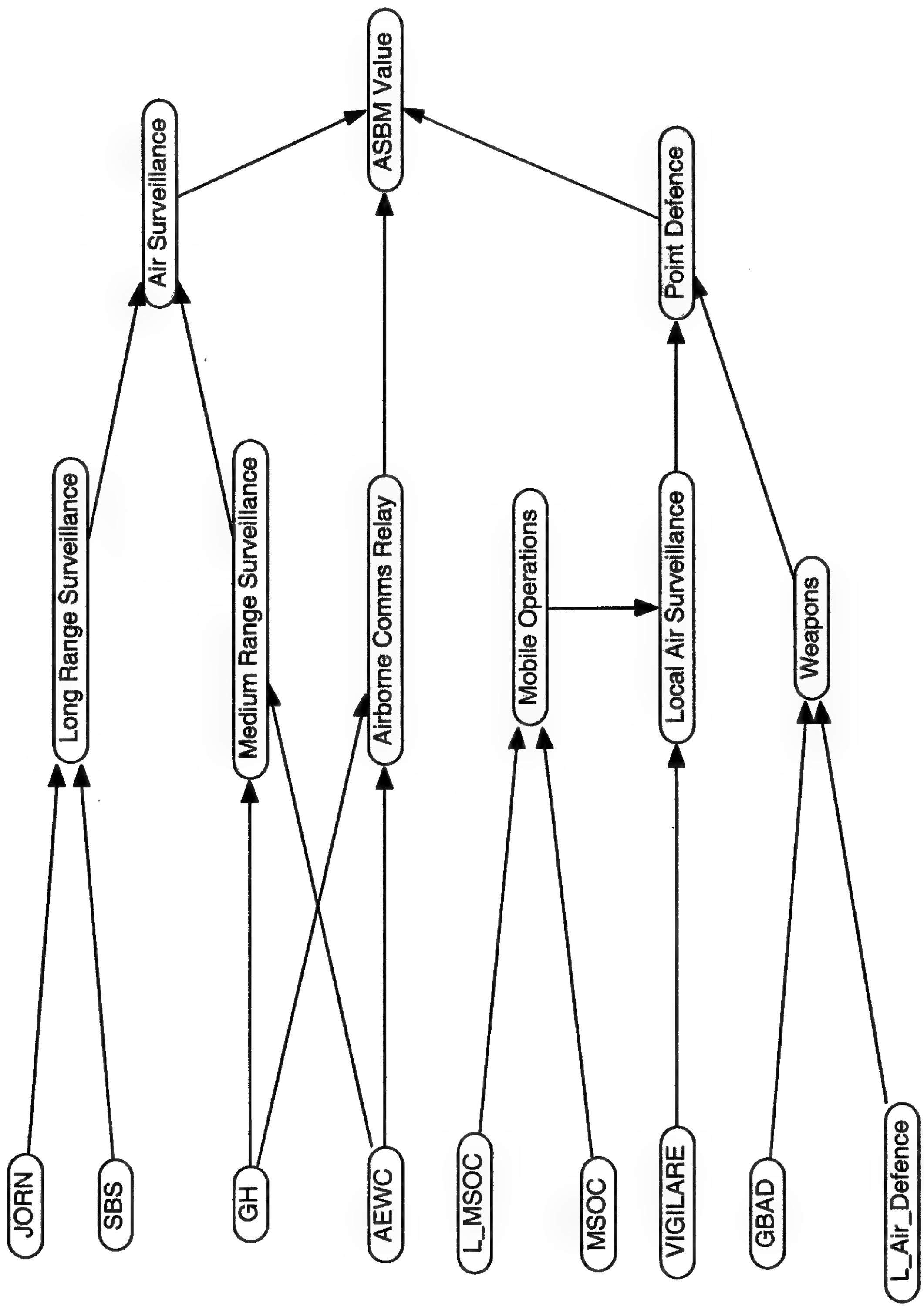

Figure 1: Hypothetical Commander's Value Network

2.1.2.1 Long Range Air Surveillance. In Table A1, it has been assumed that SBS can perform all the functions of JORN in its original state, and, furthermore, that it is about 80% reliable. On the other hand the original JORN is assumed to be 60% reliable. The upgraded JORN is assumed to be 70% reliable, and also to add additional capability beyond that provided by SBS alone. The two in combination are assumed to be 90% reliable.

2.1.2.2 Medium Range Air Surveillance. In Table A3, it has been assumed that AEW&C is 80% reliable in performing this function on its own, while Global Hawk on its own is 90% reliable. It has also been assumed that there is some degree of complementarity between the two so that the two combined provide 95% reliability.

2.1.2.3 Mobile Operations. In Table A5, it has been assumed that the legacy mobile sector operations centre (114MCRU) is 60% reliable, whereas the proposed new MSOC is 80% reliable. It assumed that there is no additional advantage in having both. A more realistic model might assign decreasing reliability with time for legacy assets, but, for this simple example, this has not been done.

2.1.2.4 Local Air Surveillance. In Table A6, it has been assumed that Vigilare alone is reliable 50% of the time, and that enhanced Vigilare is reliable 60% of the time. Combining mobile operations with Vigilare is assumed to give reliabilities of 70% and 90% for this function.

2.1.2.5 Weapons. In Table A8, it has been assumed that the legacy air defence weapons are 60% reliable, while the GBAD weapons are 90% reliable.

2.1.2.6 Air Surveillance. In Table A9, medium range surveillance on its own is assumed to be 30% reliable, as is long range surveillance on its own. The two combined are assumed to be 95% reliable.

2.1.2.7 Airborne Communications Relay. In Table A10, AEW&C on its own is assumed to be 60% reliable, while GH on its own is assumed to be 70% reliable. The two combined are assumed to be 90% reliable. Augmenting the number of AEW&C improves the reliability accordingly.

2.1.2.8 Point Defence. In Table A12, local air surveillance and effective weapons provide 90% reliability. Other combinations are totally ineffective.

2.1.2.9 Aerospace Surveillance and Battle Management. In Table A13 the asset configuration is assumed to be 100% reliable if there is adequate air surveillance, airborne communications relay and point defence. It is assumed to be 30% reliable if the airborne communication relay function is inadequate. Otherwise, it is assumed to be inadequate.

Table 3: Cost Categories of Project Phases

Cat.	Projects
1	JORN(2), MSOC, Vigilare(2), SBS(2)
2	SBS, GH, JORN(3)
3	AEW&C(2)
4	GBAD

2.1.3 Stakeholder B

Stakeholder B is assumed to be increasingly averse to total procurement costs related to ASBM that are greater than $500,000 during any given period. The project phases have been grouped into cost categories by rounding the figure cited in the DCP up to the nearest $100,000 [7]. Each category then corresponds to some multiple of $100,000. Where a figure was not available from the DCP, some guesswork was employed to deduce a suitable value. The resulting cost categories for each project phase are given in Table 3. In addition to the costs of upgrading existing assets and of introducing new assets, a cost saving of $100,000 is assumed for each asset that is retired.

A rough estimate of the total cost $\dot{C_i}$ corresponding to decision epoch t_i is obtained by summing the category numbers for each insertion or upgrade choice, and subtracting one for each retirement choice. In the case of GBAD, the procurement cost is assumed to be spread across two periods, thus two units of cost are attributed to each, rather than attributing all four units to the period immediately following the decision epoch.

The preferences that the stakeholder is assumed to have for each of the resultant cost figures are given in Table A14, where the symbolic labels $c_0, \ldots, c_{10}$ correspond to values of $0–$1,000,000. It can be seen that the stakeholder is assumed to be strongly averse to cost values of greater than $500,000, but equanimous towards figures below this. More realistically, the preferences should be tapered in this region, however this was not done.

2.2 Assets

In general, there is a fairly direct correspondence between projects and the assets they are destined to procure. However, for legacy assets, there is no corresponding project, and hence these need to be considered separately. The legacy assets that are assumed to form part of the ASBM asset configuration are 114MCRU, which is treated as a legacy mobile sector operations centre (L. MSOC), and legacy air defence assets (L. Air Defence).

2.3 Initial Conditions

The set of initial conditions specifies the circumstances prevailing at the outset, in particular the base-line configuration of the assets. For the ASBM case, the initial conditions are assumed to be those shown in Table 4.

Table 4: Baseline Asset Configuration

Asset	Condition(t_0^+)
AEW&C	Absent
Vigilare	Present
L. MSOC	Present
L. Air Defence	Present
GBAD	Absent
JORN	Original
SBS	Absent
GH	Absent

Table 5: Number of Decisions in each Financial Year

FY	03/04	04/05	05/06	06/07	07/08	08/09	09/10	10/11
Decisions	1	4	0	0	2	0	0	3

2.4 Decision Epochs

In order to reduce the complexity of the problem and to allow the "big picture" to emerge, consideration has been restricted to a limited number of decision epochs. Examination of the current DCP suggests that there are three key decision epochs for the set of projects in question [7]. Since there is only one decision for FY 03/04, this can most conveniently be combined with those for FY 04/05. The decision epochs that result, and the projects each concerns, are listed in Table 6.

The choices that it is possible to make at each of these decision epochs are listed in Table 7. The legacy assets are assumed to have reached the end of their useful life by epoch t_3, and thus are unconditionally retired at this point. To concord with the information in the DCP, it is assumed that, although the earliest that the decision to acquire the GBAD system may made is at epoch t_1, the earliest that the system will be available is period t_2^+. No matter what decision is made, it will not be available for period t_1^+, hence there is no decision to be made concerning it at epoch t_2.

3 Results

The constraints and stakeholder preferences listed above were manually compiled into the form of a BBN. The options for the decision epochs are assumed to be constrained

Table 6: Selected Decision Epochs

Epoch	FY	Decisions
t_0	02/03	—
t_1	03/04, 04/05	MSOC, GBAD, JORN(2), SBS, GH
t_2	07/08	AEW&C(2), Vigilare(2)
t_3	10/11	SBS(2), GH(2), JORN(3)

Table 7: Possible Actions by Asset and Epoch

Asset / Epoch	t_1	t_2	t_3
AEW&C	—	{Augment by 2, Augment by 3, Withdraw}	{Augment by 2, Augment by 3, Withdraw}
Vigilare	Withdraw	{Withdraw, Enhance}	{Withdraw, Enhance}
L. MSOC	Withdraw	Withdraw	—
MSOC	Insert	{Insert, Withdraw}	{Insert, Withdraw}
L. Air Defence	Withdraw	Withdraw	—
GBAD	—	—	Withdraw
JORN	{Upgrade 1, Withdraw}	{Upgrade 1, Withdraw}	{Upgrade 1, Upgrade 2, Withdraw}
SBS	Insert	{Insert, Withdraw}	{Insert, Upgrade, Withdraw}
GH	Insert	{Insert, Withdraw}	{Insert, Withdraw}

only by the asset configuration for the immediately preceding period. In this example, no additional configurational constraints were needed because each of the assets was assumed to be capable of operating in isolation from the rest. The preferences of the two stakeholders were given equal weight.

The value network of Section 2.1.2 was duplicated three times, once for each of the periods under consideration. Slight modifications were made each time to reflect the different sets of asset conditions that are possible for each period. Value network fragments representing Stakeholder B's preferences for the costs associated with each decision epoch were also included. The resulting network appears in Figure 2. The "Netica" BBN software application was used to produce the results presented below [9].

3.1 Marginal Credibilities

Figure 2 shows the marginal credibilities for each node condition in the network, contingent on the event that both stakeholders are satisfied for each decision epoch and period. Note that the credibility figures have been given in the form of percentages. The results that were obtained are also listed in Tables B1–B9 in Appendix B and summarised in colour-coded form in Table 8. A key for the colour highlighting used in Table 8 is given in Table 9.

The marginal credibilities provide a concise characterisation of the entire ensemble of asset configuration trajectories. Appendix C provides an example of the kind of sensitivity analysis that can be performed for individual nodes.

3.2 Most Credible Trajectory

Unlike computing the marginal credibilities, computing the most credible evolution of the force structure results in one best or several distinct, equally good, asset configuration trajectories. In this example, it happens that a unique answer is obtained. Figure 3 shows the resulting most credible asset configuration trajectory into the future. In this mode of inference, the figures for the asset condition credibilities shown on the diagram do not sum to one. An asset's condition in the configuration for a particular period is the one for which the assigned credibility is 100%.

The result is also presented in Table 10. If this were to be the asset configuration trajectory to which it was aspired, then the decision that should be made at the forthcoming decision epoch would be the t_1 option for this particular evolution. However, as will be explained in the next section, there are some arguments in favour of making a more subtle selection.

A noteworthy feature of this solution is that it recommends that the MSOC be withdrawn for period 2 and re-inserted for period 3. This counter-intuitive result can be attributed to the large amount of slack in the expenditure for period 3. This means that there is no penalty for the cost of re-inserting the asset. As remarked earlier, the initial portion of the cost preference curve should, more realistically, be tapered rather than flat. Also, in a more complete model, the slack expenditure may be expected to be taken up with other projects.

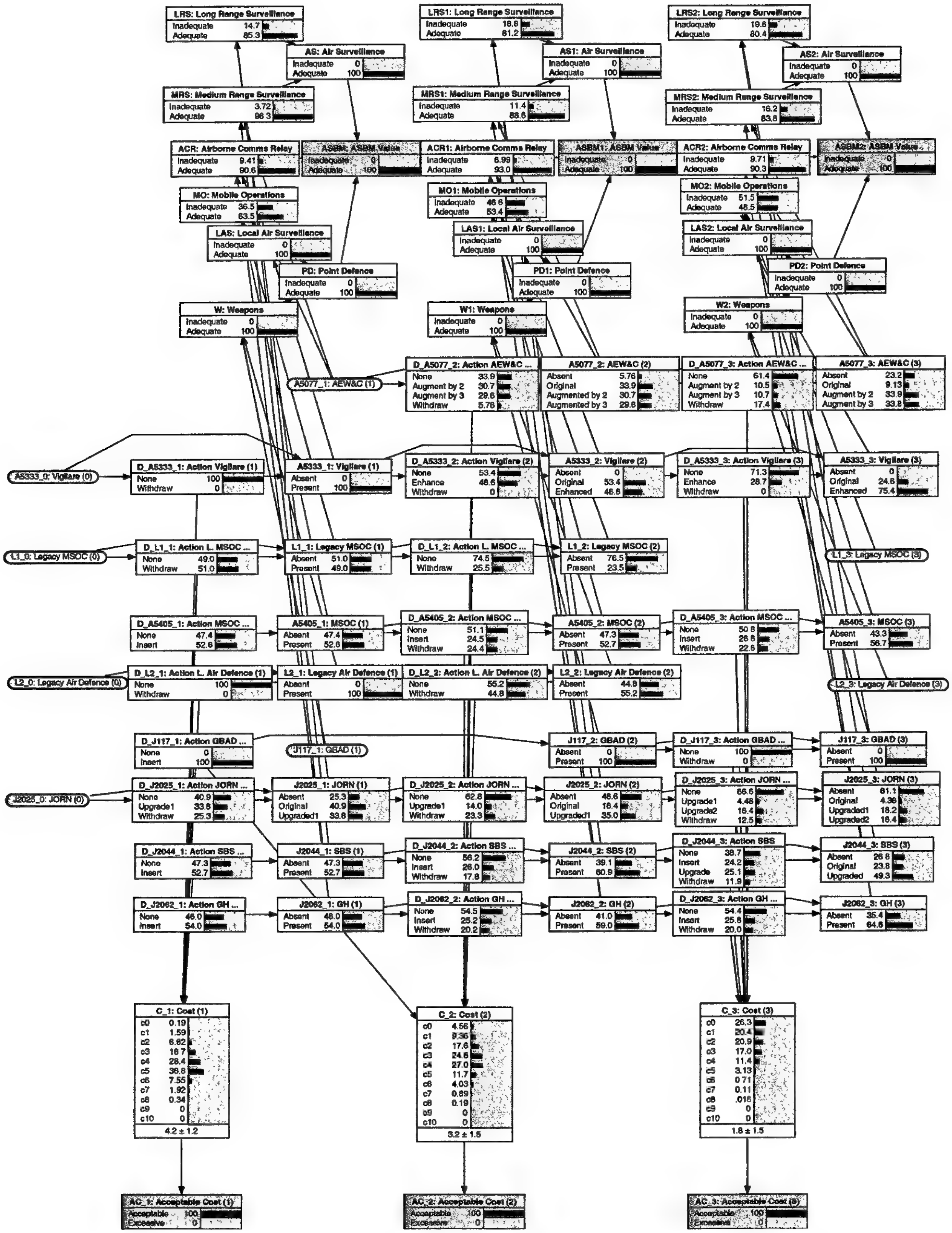

Figure 2: Belief Network showing Marginal Credibilities

Table 8: Colour-coded Marginal Credibilities

Asset / Period	t_0^+	t_1^+	t_2^+	t_3^+
AEW&C	Absent Present	Absent Present	Absent Original Augmented by 2 Augmented by 3	Absent Original Augmented by 2 Augmented by 3
Vigilare	Absent Present	Absent Present	Absent Original Enhanced	Absent Original Enhanced
L. MSOC	Absent Present	Absent Present	Absent Present	Absent Present
MSOC	Absent Present	Absent Present	Absent Present	Absent Present
L. Air Defence	Absent Present	Absent Present	Absent Present	Absent Present
GBAD	Absent Present	Absent Present	Absent Present	Absent Present
JORN	Absent Present	Absent Original Upgraded 1	Absent Original Upgraded 1	Absent Original Upgraded 1 Upgraded 2
SBS	Absent Present	Absent Present	Absent Present	Absent Original Upgraded
GH	Absent Present	Absent Present	Absent Present	Absent Present

Table 9: Colour Key

Range	Colour
0–0.1$^-$	
0.1–0.2$^-$	
0.2–0.3$^-$	
0.3–0.4$^-$	
0.4–0.5$^-$	
0.5–0.6$^-$	
0.6–0.7$^-$	
0.7–0.8$^-$	
0.8–0.9$^-$	
0.9–1.0$^-$	
1.0	

Table 10: Most Credible Trajectory

Asset	t_0^+	t_1^+	t_2^+	t_3^+
AEW&C	Absent	Present	Augmented by 3	Augmented by 3
Vigilare	Present	Present	Enhanced	Enhanced
L. MSOC	Present	Absent	Absent	Absent
MSOC	Absent	Present	Absent	Present
L. Air Defence	Present	Present	Present	Absent
GBAD	Absent	Absent	Present	Present
JORN	Present	Absent	Absent	Absent
SBS	Absent	Present	Present	Upgraded
GH	Absent	Present	Present	Present

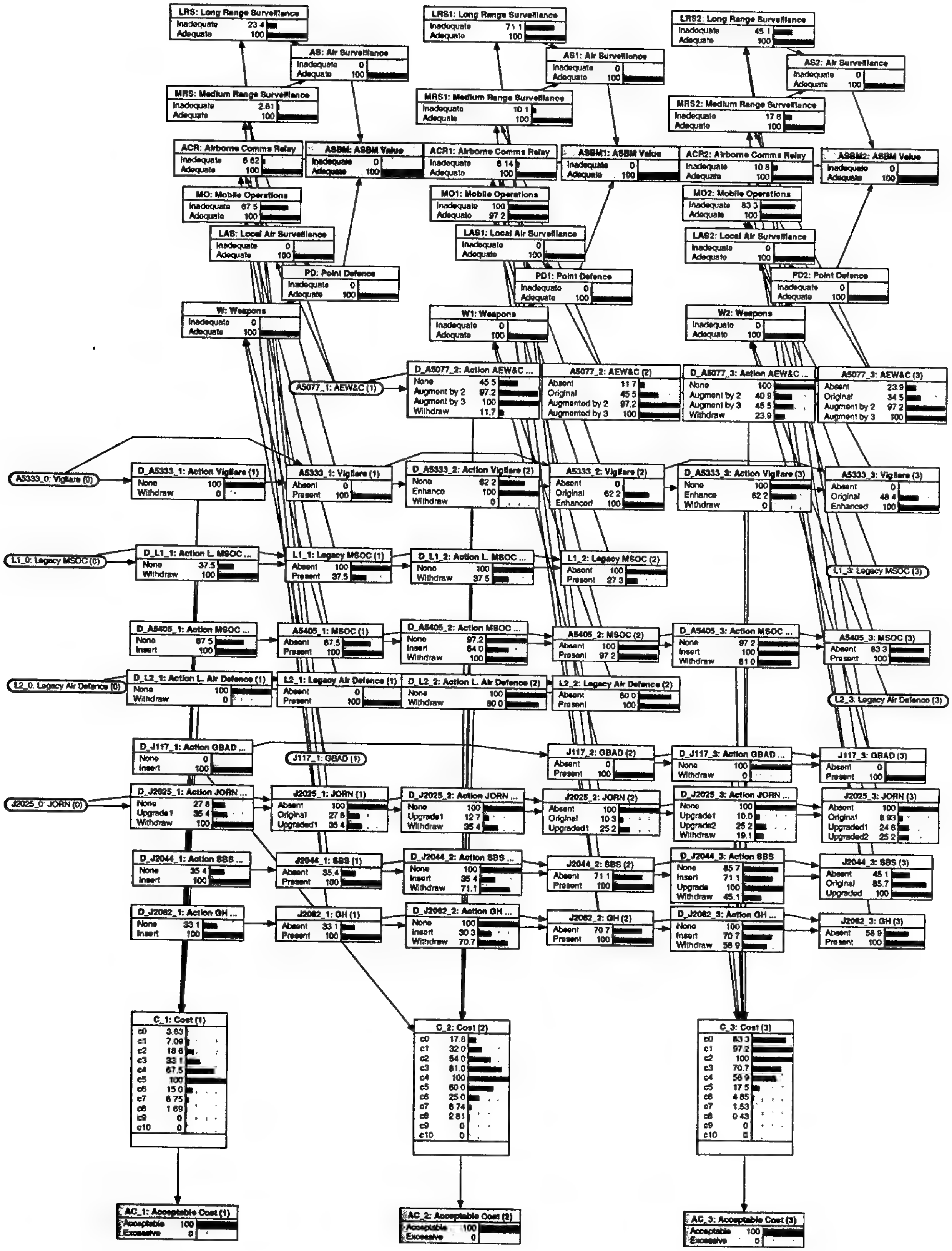

Figure 3: Belief Network showing Most Credible Trajectory

Table 11: Best Prospects Decision

Asset	Action(t_1)
AEW&C	—
Vigilare	None
L. MSOC	None
MSOC	Insert
L. Air Defence	None
GBAD	Insert
JORN	None
SBS	None
GH	Insert

3.3 Best Prospects Decision

It may reasonably be assumed that it is only ever necessary to actually *commit* to an option for the first, impending decision epoch. The best prospects decision is defined here as the selection of the most credible option for the first decision epoch t_1 over the entire ensemble of asset configuration trajectories. This option is not, in general, the same as the t_1 option for the most credible trajectory.

The reason for recommending the best prospects option, rather than the t_1 option for the most credible trajectory, is that choosing this should usually result in there being more relatively high credibility alternative trajectories on into the future, thus providing greater flexibility as stakeholder needs and preferences undergo future revision. Consequently, the best prospects decision sacrifices some initial credibility about the alternative that is selected in the interests of greater future flexibility. Unfortunately, the software that was used does not support the direct calculation of this option. However, with some additional manual manipulation it is possible to find it fairly readily. The best prospects option that was obtained in this way is given in Table 11.

Given a best prospects decision for t_1, it is then of interest to determine the most credible subsequent asset configuration trajectory in order to provide a provisional road-map for the way ahead. The BBN in which this calculation is performed is shown in Figure 4, and the results are summarised in Table 12. The asset conditions which differ from those for the most credible trajectory overall are shown emphasised *thus*. This trajectory is less credible than the most credible trajectory by a factor of 7. For the best prospects decision to be worthwhile, this figure would need to be less than the fluctuations in credibility anticipated to be brought about by future changes in the value networks.

4 Conclusion

This report has provided an example of the application of a Force Level Systems Engineering decision support method based on Bayesian Belief Network techniques to a collection of projects related to Aerospace Surveillance and Battle Management. It illustrates the kind of decision problem that can be solved by such means, and the types and quantity of information required to do so.

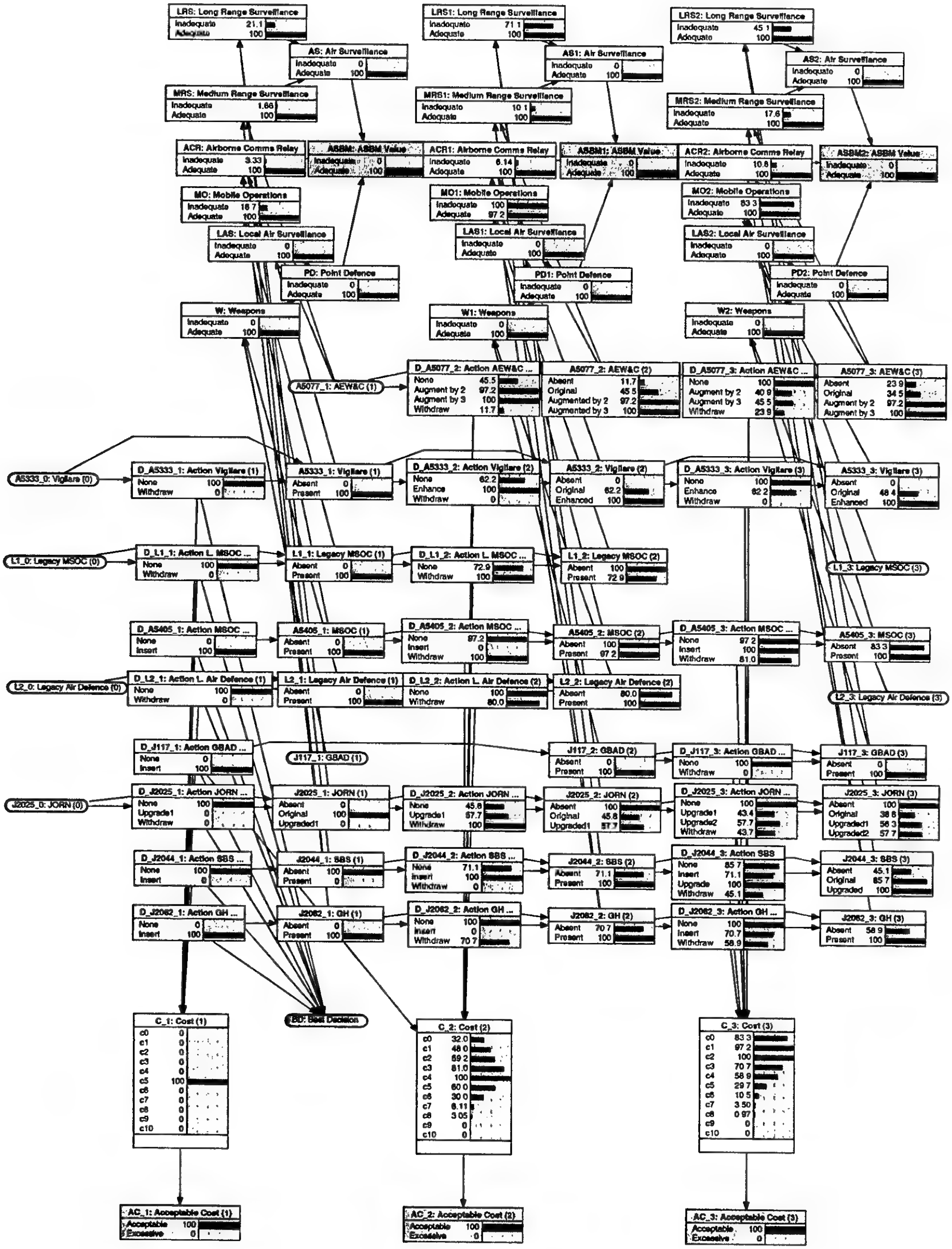

Figure 4: Belief Network showing Most Credible Trajectory for Best Prospects Decision

Table 12: Most Credible Trajectory for Best Prospects Decision

Asset	t_0^+	t_1^+	t_2^+	t_3^+
AEW&C	Absent	Present	Augmented by 3	Augmented by 3
Vigilare	Present	Present	Enhanced	Enhanced
L. MSOC	Present	*Present*	Absent	Absent
MSOC	Absent	Present	Absent	Present
L. Air Defence	Present	Present	Present	Absent
GBAD	Absent	Absent	Present	Present
JORN	Present	*Original*	Absent	Absent
SBS	Absent	*Absent*	Present	Upgraded
GH	Absent	Present	Present	Present

However, given the severely limited information on which the analysis was based, the results that were obtained are of a highly tentative nature. The more timely availability of more detailed information might have permitted the development of a more realistic model and, consequently, might have yielded results in which a greater degree of confidence could be held. The more comprehensive information that has since become available would also need to be supplemented with some direct elicitation of the pertinent stakeholders' preferences in order to properly apply the method.

Furthermore, to employ the method to its greatest advantage, the Aerospace Surveillance and Battle Management projects would need to be considered in conjunction with the other major projects, such as Air 6000 and Sea 4000, with which they are intimately intertwined.

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Appendix A Value Tables

This appendix contains tables listing the conditional credibility values used in the value networks.

Table A1: Long Range Air Surveillance (LRS), Periods 1&2

JORN	SBS	Inadequate	Adequate
Absent	Absent	1	0
Absent	Present	0.2	0.8
Original	Absent	0.4	0.6
Original	Present	0.2	0.8
Upgraded1	Absent	0.3	0.7
Upgraded1	Present	0.1	0.9

Table A2: Long Range Air Surveillance (LRS), Period 3

JORN	SBS	Inadequate	Adequate
Absent	Absent	1	0
Absent	Original	0.4	0.6
Absent	Upgraded	0.3	0.7
Original	Absent	0.5	0.5
Original	Original	0.25	0.75
Original	Upgraded	0.2	0.8
Upgraded1	Absent	0.4	0.6
Upgraded1	Original	0.2	0.8
Upgraded1	Upgraded	0.1	0.9
Upgraded2	Absent	0.3	0.7
Upgraded2	Original	0.1	0.9
Upgraded2	Upgraded	0.05	0.95

Table A3: Medium Range Air Surveillance (MRS), Period 1

GH	AEWC	Inadequate	Adequate
Absent	Absent	1	0
Absent	Present	0.2	0.8
Present	Absent	0.1	0.9
Present	Present	0.05	0.95

Table A4: Medium Range Air Surveillance (MRS), Periods 2&3

GH	AEWC	Inadequate	Adequate
Absent	Absent	1	0
Absent	Original	0.6	0.4
Absent	Augmented by 2	0.4	0.6
Absent	Augmented by 3	0.3	0.7
Present	Absent	0.7	0.3
Present	Original	0.2	0.8
Present	Augmented by 2	0.1	0.9
Present	Augmented by 3	0.05	0.95

Table A5: Mobile Operations (MO)

L_MSOC	MSOC	Inadequate	Adequate
Absent	Absent	1	0
Absent	Present	0.2	0.8
Present	Absent	0.4	0.6
Present	Present	0.2	0.8

Table A6: Local Air Surveillance (LAS), Period 1

VIGILARE	MO	Inadequate	Adequate
Absent	Inadequate	1	0
Absent	Adequate	0.6	0.4
Present	Inadequate	0.4	0.6
Present	Adequate	0.1	0.9

Table A7: Local Air Surveillance (LAS), Periods 2&3

MO	VIGILARE	Inadequate	Adequate
Inadequate	Absent	1	0
Inadequate	Original	0.5	0.5
Inadequate	Enhanced	0.4	0.6
Adequate	Absent	1	0
Adequate	Original	0.3	0.7
Adequate	Enhanced	0.1	0.9

Table A8: Weapons (W)

GBAD	L_Air_Defence	Inadequate	Adequate
Absent	Absent	1	0
Absent	Present	0.4	0.6
Present	Absent	0.1	0.9
Present	Present	0.1	0.9

Table A9: Air Surveillance (AS)

LRS	MRS	Inadequate	Adequate
Inadequate	Inadequate	1	0
Inadequate	Adequate	0.7	0.3
Adequate	Inadequate	0.7	0.3
Adequate	Adequate	0.05	0.95

Table A10: Airborne Communications Relay (ACR), Period 1

GH	AEWC	Inadequate	Adequate
Absent	Absent	1	0
Absent	Present	0.4	0.6
Present	Absent	0.3	0.7
Present	Present	0.1	0.9

Table A11: Airborne Communications Relay (ACR), Periods 2&3

GH	AEWC	Inadequate	Adequate
Absent	Absent	1	0
Absent	Original	0.4	0.6
Absent	Augmented by 2	0.3	0.7
Absent	Augmented by 3	0.2	0.8
Present	Absent	0.3	0.7
Present	Original	0.1	0.9
Present	Augmented by 2	0.05	0.95
Present	Augmented by 3	0	1

Table A12: Point Defence (PD)

LAS	W	Inadequate	Adequate
Inadequate	Inadequate	1	0
Inadequate	Adequate	1	0
Adequate	Inadequate	1	0
Adequate	Adequate	0.1	0.9

Table A13: Aerospace Surveillance and Battle Management (ASBM)

AS	ACR	PD	Inadequate	Adequate
Inadequate	Inadequate	Inadequate	1	0
Inadequate	Inadequate	Adequate	1	0
Inadequate	Adequate	Inadequate	1	0
Inadequate	Adequate	Adequate	1	0
Adequate	Inadequate	Inadequate	1	0
Adequate	Inadequate	Adequate	0.7	0.3
Adequate	Adequate	Inadequate	1	0
Adequate	Adequate	Adequate	0	1

Table A14: Acceptable Cost (C)

C	Acceptable	Excessive
c0	1	0
c1	1	0
c2	1	0
c3	1	0
c4	1	0
c5	1	0
c6	0.25	0.75
c7	0.1	0.9
c8	0.05	0.95
c9	0	1
c10	0	1

Appendix B Marginal Credibilities

This appendix contains tables listing the marginal credibilities of the conditions of each asset by period. Since the figures are approximate, excess significant figures should be disregarded.

Table B1: A5077 AEW&C Marginal Credibilities

Condition	t_0^+	t_1^+	t_2^+	t_3^+
Absent	1	0	0.057579	0.23158
Original	0	1	0.33899	0.091322
Augmented by 2	0	0	0.307	0.33863
Augmented by 3	0	0	0.29643	0.33847

Table B2: A5333 Vigilare Marginal Credibilities

Condition	t_0^+	t_1^+	t_2^+	t_3^+
Absent	0	0	0	0
Original	1	1	0.53362	0.2464
Enhanced	0	0	0.46638	0.7536

Table B3: L1 Legacy MSOC Marginal Credibilities

Condition	t_0^+	t_1^+	t_2^+	t_3^+
Absent	0	0.5099	0.76494	1
Present	1	0.4901	0.23506	0

Table B4: A5405 MSOC Marginal Credibilities

Condition	t_0^+	t_1^+	t_2^+	t_3^+
Absent	1	0.47434	0.47317	0.43294
Present	0	0.52566	0.52683	0.56706

Table B5: L2 Legacy Air Defence Marginal Credibilities

Condition	t_0^+	t_1^+	t_2^+	t_3^+
Absent	0	0	0.44767	1
Present	1	1	0.55233	0

Table B6: J117 GBAD Marginal Credibilities

Condition	t_0^+	t_1^+	t_2^+	t_3^+
Absent	1	1	0	0
Present	0	0	1	1

Table B7: J2025 JORN Marginal Credibilities

Condition	t_0^+	t_1^+	t_2^+	t_3^+
Absent	0	0.25301	0.48596	0.6111
Original	1	0.40872	0.16354	0.04358
Upgraded1	0	0.33827	0.3505	0.18154
Upgraded2	0	0	0	0.16379

Table B8: J2044 SBS Marginal Credibilities

Condition	t_0^+	t_1^+	t_2^+	t_3^+
Absent	1	0.47294	0.39141	0.26826
Original	0	0.52706	0.60859	0.23831
Upgraded	0	0	0	0.49344

Table B9: J2062 GH Marginal Credibilities

Condition	t_0^+	t_1^+	t_2^+	t_3^+
Absent	1	0.45979	0.40981	0.35398
Present	0	0.54021	0.59019	0.64602

Appendix C Sensitivity Analysis for Node D_J2025_1

This appendix provides an example of the kind of sensitivity analysis that may be performed. The target variable that has been chosen for this example is decision taken on JORN at epoch 1, which has the designation D_J2025_1. The numerical column on the left shows the mutual entropy reduction, in bits, that can be achieved by a finding for the second variable in the list. The column on the right shows the relative decrease in variance that may be achieved.

The results show that the variable that has most influence, outside the trivial case of itself, is the condition of the asset during period 1. This must self-evidently be the case, since the condition of the asset is a deterministic function of the decision variable. The next most influential variables are the condition and decision variables for the same asset for subsequent periods and epochs. After these, as might be expected, the cost for period 1 becomes most significant. Further down the list are variables connected with related projects, such as space-based surveillance (J2044) and Global Hawk (J2062).

Hence, it is apparent that sensitivity analysis such as this can provide some useful insights into the most important connections between the various projects. These connections might be useful in suggesting groups of projects that should lie within the realm of responsibility of a single chain of management, for example.

```
Sensitivity of 'D_J2025_1' due to a finding at another node:

Node                 Mutual     Variance of
----                 Info       Beliefs
J2025_1              1.55821    0.4321961
D_J2025_1            1.55821    0.4321961
J2025_2              0.50144    0.0945923
D_J2025_2            0.34608    0.0638003
J2025_3              0.25947    0.0304327
D_J2025_3            0.22037    0.0268885
C_1                  0.07364    0.0111973
D_J2044_1            0.06979    0.0073491
J2044_1              0.06979    0.0073491
LRS                  0.03130    0.0048546
J2044_2              0.02182    0.0024708
D_J2044_2            0.02032    0.0023851
LRS1                 0.01823    0.0027606
J2044_3              0.01335    0.0015787
D_J2062_1            0.01074    0.0013785
J2062_1              0.01074    0.0013785
D_J2044_3            0.01005    0.0013044
LRS2                 0.00887    0.0012690
C_3                  0.00810    0.0009089
D_J2062_2            0.00546    0.0007227
```

C_2	0.00477	0.0005939
D_L1_1	0.00199	0.0003539
L1_1	0.00199	0.0003539
A5405_1	0.00160	0.0002951
D_A5405_1	0.00160	0.0002951
D_A5405_2	0.00087	0.0001648
MRS2	0.00075	0.0000895
MRS1	0.00072	0.0000799
L1_2	0.00071	0.0001130
D_L1_2	0.00069	0.0001293
MRS	0.00066	0.0000751
ACR	0.00056	0.0000742
D_A5077_2	0.00052	0.0000620
A5077_2	0.00052	0.0000620
A5077_3	0.00052	0.0000645
MO	0.00028	0.0000311
ACR2	0.00016	0.0000191
D_A5077_3	0.00010	0.0000126
J2062_3	0.00009	0.0000119
L2_2	0.00009	0.0000113
D_L2_2	0.00009	0.0000113
MO1	0.00006	0.0000084
A5333_3	0.00005	0.0000066
ACR1	0.00004	0.0000050
J2062_2	0.00004	0.0000049
A5405_3	0.00004	0.0000048
A5333_2	0.00004	0.0000045
D_A5333_2	0.00004	0.0000045
MO2	0.00003	0.0000035
D_J2062_3	0.00002	0.0000036
A5405_2	0.00001	0.0000015
D_A5405_3	0.00001	0.0000007
D_A5333_3	0.00000	0.0000000
PD2	0.00000	0.0000000
ASBM1	0.00000	0.0000000
AC_1	0.00000	0.0000000
AS1	0.00000	0.0000000
L2_1	0.00000	0.0000000
ASBM2	0.00000	0.0000000
D_A5333_1	0.00000	0.0000000
AS2	0.00000	0.0000000
A5333_1	0.00000	0.0000000
D_J117_1	0.00000	0.0000000
D_L2_1	0.00000	0.0000000
LAS	0.00000	0.0000000
PD1	0.00000	0.0000000
W1	0.00000	0.0000000

PD	0.00000	0.0000000
LAS2	0.00000	0.0000000
J117_2	0.00000	0.0000000
AC_2	0.00000	0.0000000
D_J117_3	0.00000	0.0000000
W2	0.00000	0.0000000
AC_3	0.00000	0.0000000
J117_3	0.00000	0.0000000
ASBM	0.00000	0.0000000
AS	0.00000	0.0000000
LAS1	0.00000	0.0000000
W	0.00000	0.0000000

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R. J. Staker

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19. ABSTRACT

This report demonstrates the application of a Bayesian Belief Network decision support method for Force Level Systems Engineering to a collection of projects related to Aerospace Surveillance and Battle Management. The proposed method is used to determine the most credible combinations of these projects, and the most plausible evolutions of the force structures that they deliver over time. Since the analysis is based on strictly limited information, the results that are obtained are of a highly tentative nature. Nevertheless, the potential utility of such an approach is convincingly demonstrated.

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